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Short Communication

High-efficiency photovoltaic technology including thermoelectric generation

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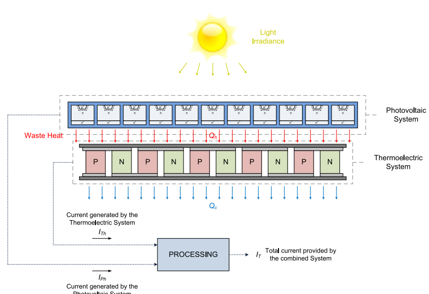
HIGHLIGHTS

- Development of a model which relates photovoltaic technology with thermoelectrics.
- Using temperature gradient to feed a thermoelectric structure for power generation.
- Theoretical and practical increase of overall efficiency under extreme conditions.
- Maximum power is greater when using thermoelectric cells in the system.

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays, photovoltaic solar energy is a clean and reliable source for producing electric power. Most photovoltaic systems have been designed and built up for use in applications with low power requirements. The efficiency of solar cells is quite low, obtaining best results in monocrystalline silicon structures, with an efficiency of about 18%. When temperature rises, photovoltaic cell efficiency decreases, given that the short-circuit current is slightly increased, and the open-circuit voltage, fill factor and power output are reduced. To ensure that this does not affect performance, this paper describes how to interconnect photovoltaic and thermoelectric technology into a single structure. The temperature gradient in the solar panel is used to supply thermoelectric cells, which generate electricity, achieving a positive contribution to the total balance of the complete system.

1. Introduction

In light of the large current energy demands, solar energy is considered a feasible solution for the future, and an answer to global warming. Furthermore, solar energy is beneficial as it is clean, renewable, and environmental-friendly.

Currently, photovoltaic systems convert solar energy directly into electricity without leading to pollution emissions to the atmosphere. Although since their beginning in 1839 [1] a significant progress has been made, still much work needs to be done in order to increase efficiency and reduce economic costs.

The implementation of a system that combines photovoltaic and thermal technology can be a good way of using residual heat and increasing efficiency. The use of a thermoelectric structure can directly convert residual thermal energy into electrical energy through the temperature difference between the two faces of a solar panel. In addition, a thermal structure has no moving parts

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Nomenclature

T	absolute temperature (K)
Q_c	absorbed heat flow in the thermoelectric system (W)
A	area (m^2)
k	Boltzmann's constant (J K^{-1})
m	coefficient of resistance variation (dimensionless)
T_c	cold side temperature in the thermoelectric system (K)
Q_h	dissipated heat flow in the thermoelectric system (W)
q	electrical charge on the electron (C)
I	electrical current in the thermoelectric system (A)
T_{ct}	experimental temperature of the photovoltaic system
R	general resistance (Ω)
T_h	hot side temperature in the thermoelectric system (K)
n	ideality factor of the solar cell model (dimensionless)
R_0	initial value of general resistance (Ω)
V_{oc}	open circuit voltage of the solar cell model (V)
I_λ	photocurrent proportional to the intensity of solar radiation (A)
R_p	resistance that represents the imperfections in the p–n junction (Ω)
T_0	room temperature that surrounds the thermal structure (K)
I_s	saturation current of the p–n junction of the solar cell model (A)
R_s	series resistance of the solar cell model (Ω)
I_{sc}	short circuit electrical current of the solar cell model (A)
$T_{1,2,3,4,5,6}$	temperatures in the different structure interfaces (K)
T_{ts}	temperature difference applied in the experimental thermoelectric system
V_T	thermal voltage (mV)
N	total number of pellets in the thermoelectric structure

Greek symbols

ρ	electrical resistivity (Ω cm)
Δ	Laplace operator
α	Seebeck coefficient (μV K^{-1})
κ	thermal conductivity (mW cm^{-1} K^{-1})
κ_{cc}	thermal conductivity of the ceramic cold face (mW cm^{-1} K^{-1})
κ_{ch}	thermal conductivity of the ceramic hot face (mW cm^{-1} K^{-1})
κ_m	thermal conductivity of the metal contacts between semiconductors (mW cm^{-1} K^{-1})
κ_s	thermal conductivity of the semiconductor used (mW cm^{-1} K^{-1})
κ_0	thermal conductivity on the ceramic surface in contact with air (mW cm^{-1} K^{-1})

Subscripts

c	cold temperature and heat flow absorbed
h	hot temperature and heat flow rejected
0	initial value
1,2,3,4,5,6	indicates the different internal interfaces of a thermoelectric device
oc	open circuit
sc	short circuit
Ph	related to photovoltaic system
Th	related to thermoelectric system

and is completely quiet and clean, and can be used for years as a complement to photovoltaic systems.

It is interesting to note that the use of nanotechnology in the thermal solar industry is currently seeing a performance boost in these application fields, and therefore the use of these two technologies combined will provide a better efficiency.

2. Typical solar cell

A typical construction of a solar cell is shown in Fig. 1 [2]. It should be noted that the electrical contact to the semiconductor material is always made via a metal n+ (or p+) junction; this is found to be the most convenient way of providing an ohm contact.

The basic electrical equivalent model of the photovoltaic cell is shown in Fig. 2 [3]. The most important parameters of this model are the electrical short-circuit current I_{sc}; the open circuit voltage V_{oc}; the saturation current of the p–n junction of the cell, I_s; the series resistance R_s; the ideality factor n; and the thermal voltage, which depends on absolute temperature T, and can be expressed as $V_T = k \cdot T/q$, with $k = 1.38 \times 10^{-23}$ J K^{-1}; $T = 298.16$ K; and $q = 1.6 \times 10^{-19}$ C.

The photocurrent I_λ proportional to the intensity of solar radiation incident on the device is generated by the current source. The p–n junction solar cell is represented by a direct polarised diode. The resistance R_s represents the internal potential drop to

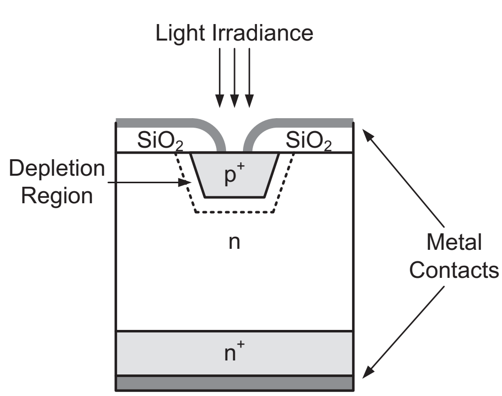

Fig. 1. Typical construction of a solar cell [2].

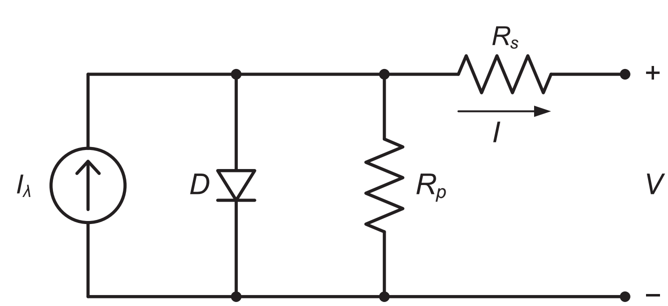

Fig. 2. Solar cell electrical model used in the investigation. R_s and R_p resistors has been included for a more realistic simulation results, by including Joule losses.

the contact terminals. The resistance R_p represents the imperfections in the p–n junction. Under these conditions, the $I(V)$ equation of the circuit can be derived directly by applying Kirchhoff's laws for electrical circuits (equation (1)) [4]. Note that the series and parallel resistance of the cell affects, basically, the fill factor and cell efficiency [5]. Following sections of this paper will show how to take advantage of those heat losses for generating electrical power.

$$I = I_\lambda - I_s\left(\exp\frac{V + R_s I}{nV_T} - 1\right) - \frac{V + R_s I}{R_P} \tag{1}$$

The series resistance R_s is the internal resistance of the cell and is due to the metallisation mesh, the contact resistance and the resistance of the semiconductor itself. There should be an agreement between the device cover and the series resistance, in such a way that when the cover factor tends to zero (metallisation mesh allowed to get more light) the series resistance increases to infinite. The parallel resistance or shunt R_p has its origin in the junction imperfections which constitute the cell, and is responsible for the current loss. The influence of temperature on the basic parameters of the photovoltaic cell is key to its working behaviour, as efficiency is increased by lowering the temperature [6], as is shown in Fig. 3.

The influence of temperature variations in the series and parallel resistance is essential to the system's global efficiency. Therefore, if the values of the resistance are based on temperature, this could be expressed in a simple way as:

$$R = R_0(1 + mT) \tag{2}$$

It is precisely on temperature T of equation (2) where the thermoelectric device could be applied to control the temperature increase in the photovoltaic cell, and thus, ensure that efficiency is maintained [7].

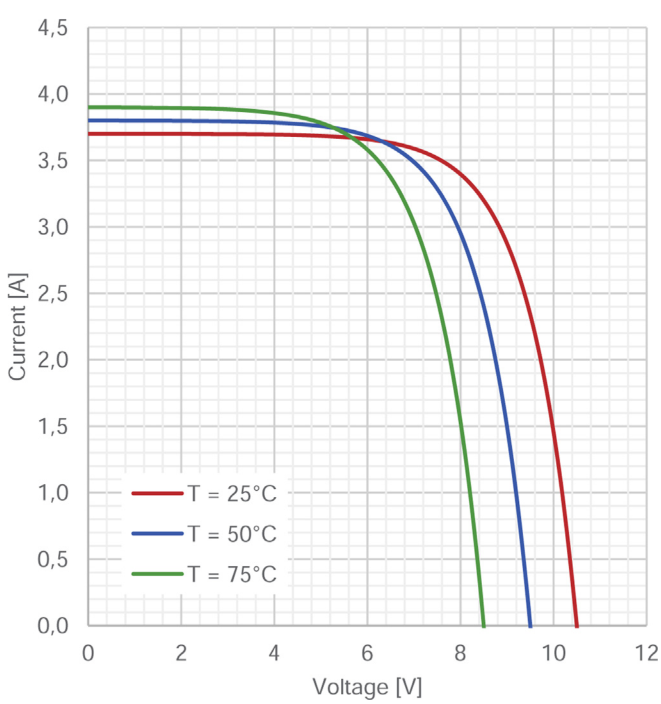

Fig. 3. Temperature influence on the photovoltaic cell. Note that when temperature of the system increases its efficiency is reduced.

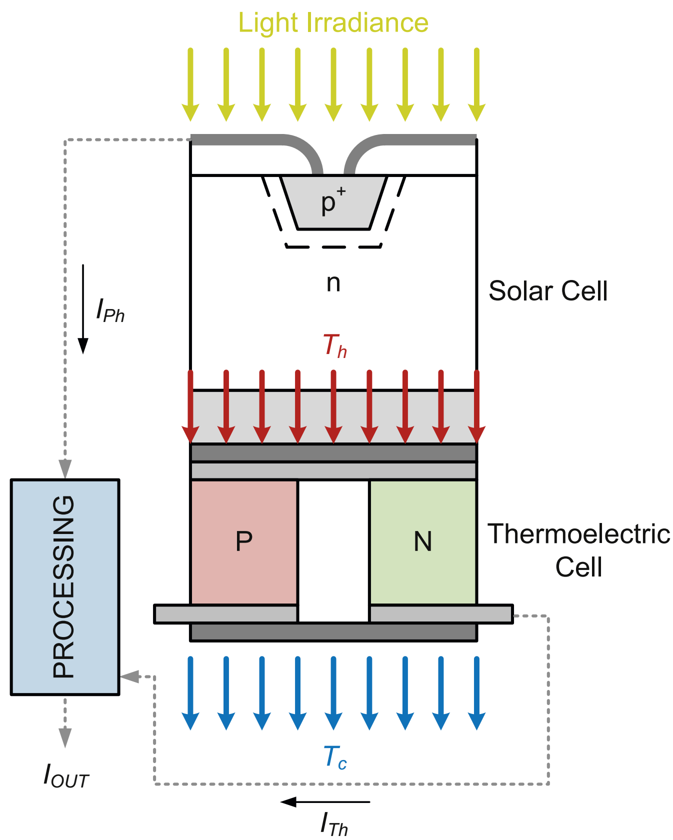

Fig. 4. Complete structure combining both technologies. The waste heat generated in the solar cell is used by the thermoelectric cell to generate electrical power and contribute in the generation system.

3. Thermoelectric and photovoltaic technology interaction

A basic scheme of the structure that includes a photovoltaic cell and a thermoelectric device is shown in Fig. 4 [8].

In general, the heat flux in a semiconductor could be expressed according to the laws of heat for the three dimensions as:

$$\Delta(\kappa\Delta T) - T(I\Delta\alpha) + I^2\rho = 0 \tag{3}$$

where κ is thermal conductivity, α is the Peltier coefficient, ρ is the electrical resistance, and ΔT is the Laplacian of temperature. In only one dimension, this could be expressed as:

$$\frac{\partial}{\partial x}\left(\kappa A\frac{\partial T}{\partial x}\right) - IT\frac{\partial\alpha}{\partial x} + I^2\rho = 0 \tag{4}$$

When a steady-state system is considered in a way that internal energy is equal to zero, the solution of the previous expression could be determined based on the heat absorbed or dissipated by the external surfaces of the semiconductor, that is:

$$\begin{bmatrix} \alpha I - \kappa & \kappa \\ -\kappa & \alpha I + \kappa \end{bmatrix} \cdot \begin{bmatrix} T_h \\ T_c \end{bmatrix} = \begin{bmatrix} Q_h - \frac{1}{2}I^2R \\ Q_c + \frac{1}{2}I^2R \end{bmatrix} \tag{5}$$

where Q_h is the dissipated heat flux; Q_c is the absorbed heat flux; R is the electrical resistance; T_h is the temperature on the hot face; and T_c is the temperature on the cold face. As shown in the electrical

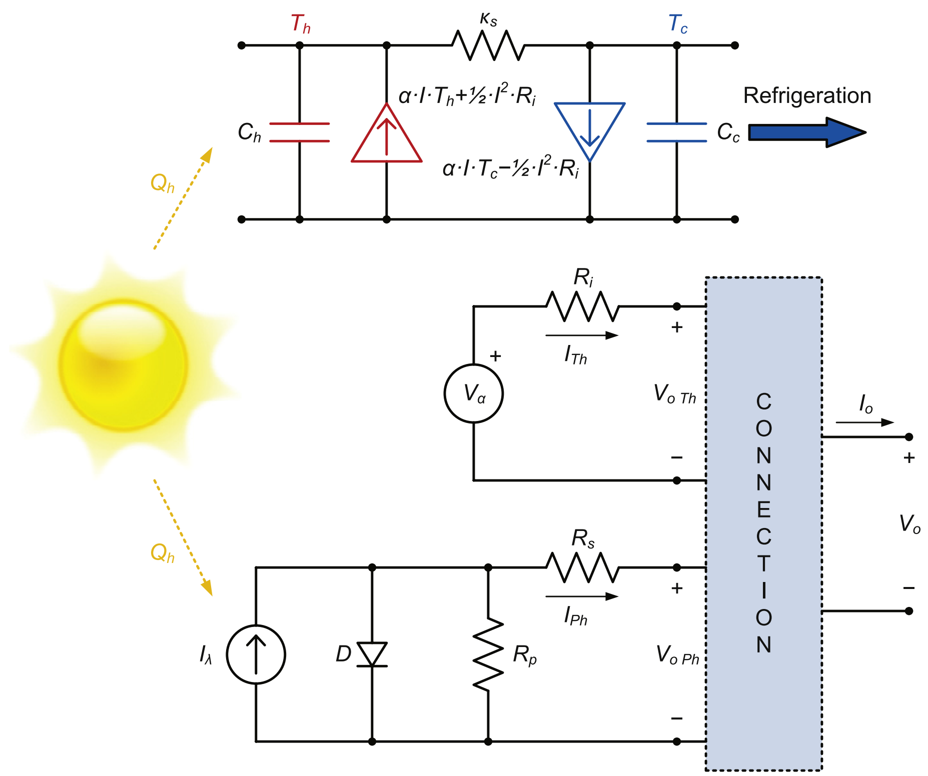

Fig. 5. Electrical model equivalent of photovoltaic and thermoelectric technologies used for simulating the complete system behaviour.

scheme of Fig. 5 [9,10], the electrical model of the basic photo-thermal structure can be depicted in a simple way.

If this study is applied to a panel, the electrical model to be used should contain all the cells that form the panel and their physical features. The top cover of the panel is made of shock-resistant tempered glass, with an optical quality that facilitates the penetration of solar radiation. The outer surface of the glass must be flat in order to avoid dust build-up, as this would reduce performance. The bottom surface of the panel must be opaque for protection against external agents, especially humidity, and should provide a strong mechanical support to the panel. Between both covers there is an encapsulation material which covers the cells and electrical connections. This material must be resistant to solar radiation, must not be affected by UV rays and must not absorb humidity. Silicon, polyvinyl and EVA (ethylene vinyl acetate) are used as encapsulation materials. This assembly is mounted on a metallic frame of anodised aluminium or stainless steel, which provides the panel with the stiffness and mechanical strength, which is needed. The frame includes the necessary holes to ensure stability. The assembly is completed with the outer electrical elements (wires, junction box).

A deeper analysis of the thermoelectric elements, which takes into account the effects generated by the different interfaces such as the ceramics, the metallic contacts of the semiconductors, and extended to the nth semiconductors and the thermoelectric cell conductors, can be expressed as shown in Fig. 6 [11] and equation (6) as a block matrix system, from which thermal and physical characteristics, including Joule effect losses, of the different parts of the thermoelectric structure (ceramic face, metal contacts between semiconductors and itself semiconductor) can be identified and configured according to the application needs.

$$\begin{bmatrix} -\kappa_0-\kappa_{cc} & \kappa_{cc} & 0 & 0 & 0 & 0 \\ \kappa_{cc} & -\kappa_{cc}-\frac{N}{2}\kappa_m & \frac{N}{2}\kappa_m & 0 & 0 & 0 \\ 0 & \frac{N}{2}\kappa_m & -N\left(\alpha I+\kappa_s+\frac{\kappa_m}{2}\right) & N\kappa_s & 0 & 0 \\ 0 & 0 & N\kappa_s & N\left(\alpha I+\kappa_s+\frac{\kappa_m}{2}\right) & \frac{N}{2}\kappa_m & 0 \\ 0 & 0 & 0 & \frac{N}{2}\kappa_m & -\kappa_{CH}-\frac{N}{2}\kappa_m & 0 \\ 0 & 0 & 0 & 0 & \kappa_{ch} & -\kappa_0-\kappa_{ch} \end{bmatrix} \cdot \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} -Q_c-\kappa_0 T_0 \\ 0 \\ \frac{N}{2}I^2\left(R_s+\frac{R_m}{2}\right) \\ -\frac{N}{2}I^2\left(R_s+\frac{R_m}{2}\right) \\ 0 \\ Q_h-\kappa_0 T_0 \end{bmatrix} \tag{6}$$

Figs. 7 and 8 show the behaviour of a combined photovoltaic and thermoelectric structure. The power over a 12 Ω nominal load increases with a ΔT in the thermoelectric structure. This behaviour is

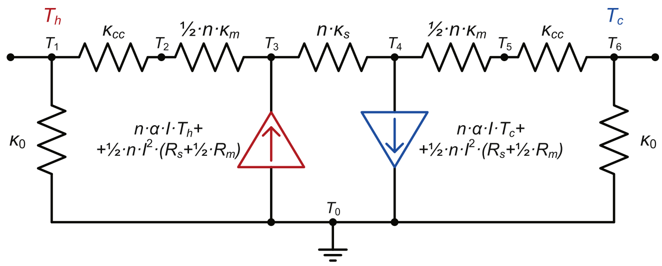

Fig. 6. Detailed electrical model equivalent of a thermoelectric device, by including the thermal resistance of ceramic face, metal contacts between semiconductors and the semiconductor.

similar to the variations applied to the serial resistance of the photovoltaic structure's electrical model. The same happens with the voltage/current curve. As can be seen in Figs. 7 and 8, when temperature increases the photovoltaic system efficiency decreases. This fact is utilized by the thermoelectric system for generating electrical power. In this way a balance between photovoltaic system losses and thermoelectric generation is reached.

4. Experimental results

In the practical application, a standard 50 Wp polycrystalline photovoltaic panel (Fig. 9) has been used, and thermoelectric devices have been applied on the rear side. This modified panel will serve as a reference to compare the efficiency and performance of the combined technology.

Three scenarios have been tested in the experiment:

- Photovoltaic panel operation in standard mode, that is without thermoelectric system integration. In this way voltage and current provided by the photovoltaic panel in normal situation by using only solar cells technology is obtained.

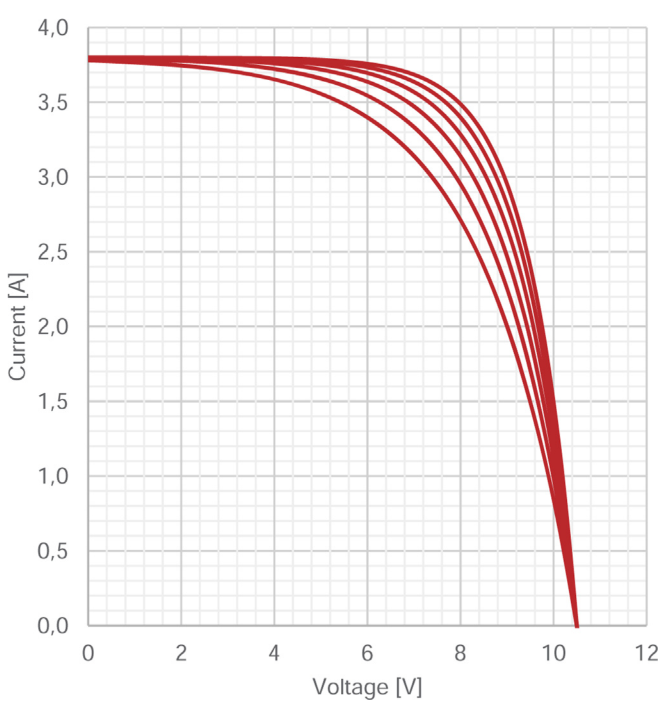

Fig. 7. Simulation of the influence of ambient temperature in the electrical power supplied by the complete system.

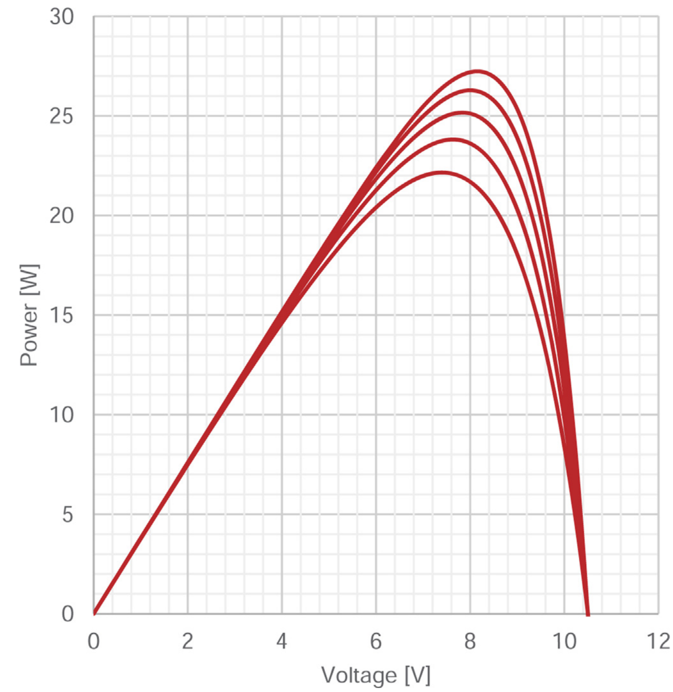

Fig. 8. Simulation of *V–I* characteristics as a function of temperature in the combined thermoelectric and photovoltaic system.

- Photovoltaic panel operation with thermoelectric modules integration. Temperature conditions are the same that in the previous case, but thermoelectric modules have been added on the rear side of photovoltaic panel. Waste heat that comes from the front panel supplies the thermoelectric modules, which will increase the electric power supplied by the combined system.
- Photovoltaic panel operation without combined thermoelectric technology with a lower ambient temperature. Expected efficiency must be greater than first scenario results.

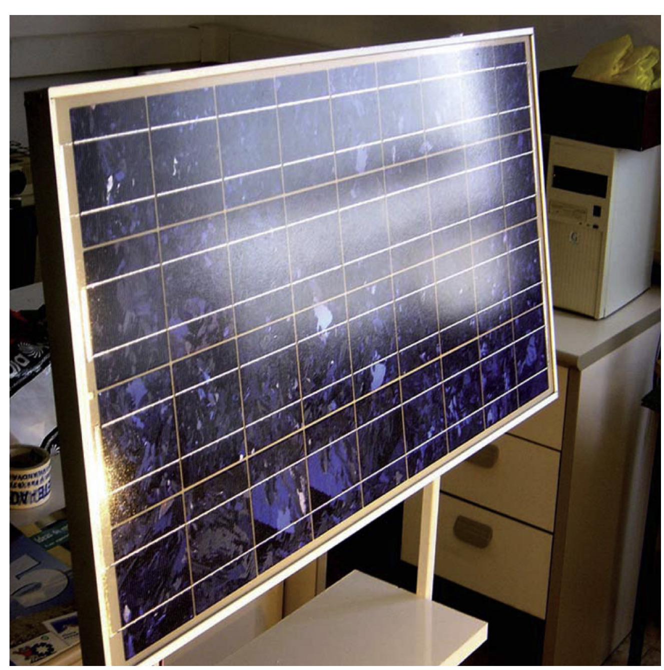

Fig. 9. Solar panel used to perform the experimental analysis of the system proposed.

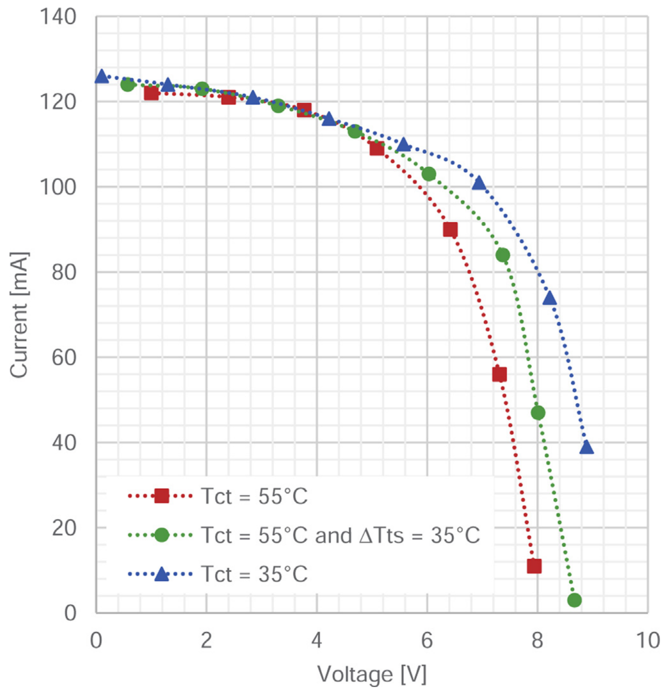

Fig. 10. Results obtained with several temperature operations and scenarios. In the same temperature conditions combined technology shows an improved performance that a simple photovoltaic system.

Fig. 10 shows experimental results obtained in the test. First and second scenarios have been tested in a temperature $T_{ct} = 55°C$. In the second one a temperature difference of $\Delta T_{ts} = 35°C$ has been applied, by obtaining an electric power greater than the standard photovoltaic system. To achieve the desired ΔT on the thermoelectric devices, some lower temperatures (20°C) have been forced, which could be obtained in real-life conditions with a good technical design. In the last scenario best results have been obtained due to a much lower system temperature.

5. Conclusions

In this paper, an electrical model has been developed combining photovoltaic technology with thermoelectric technology, for the purpose of obtaining a global efficiency increase under extreme temperature conditions.

The combination of both technologies has been tested and obtained satisfactory results, although much remains to be done in order to achieve an optimal assembly of both technologies into a single semiconductor structure.

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